

PEBBLE-BED NUCLEAR REACTOR SYSTEM PHYSICS AND FUEL UTILIZATION

An Honors Fellows Thesis

by

RYAN PATRICK KELLY

Submitted to the Honors Programs Office
Texas A&M University
in partial fulfillment of the requirements for the designation as
HONORS UNDERGRADUATE RESEARCH FELLOW

April 2011

Major: Nuclear Engineering

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ABSTRACT

Pebble-Bed Nuclear Reactor System Physics and Fuel Utilization. (April 2011)

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The Generation IV Pebble Bed Modular Reactor (PMBR) design may be used for electricity production, co-generation applications (industrial heat, hydrogen production, desalination, etc.), and could potentially eliminate some high level nuclear wastes. Because of these advantages, as well as the ability to build cost-effective small-to-medium sized reactors, this design is currently being considered for construction in many countries, from Japan, where test reactors are being analyzed, to China. The use of TRISO-coated micro-particles as a fuel in these reactors leads to multi-heterogeneity physics features that must be properly treated and accounted for. Inherent interrelationships of neutron interactions, temperature effects, and structural effects, further challenge computational evaluations of High Temperature Reactors (HTRs). The developed models and computational techniques have to be validated in code-to-code and, most importantly, code-to-experiment benchmark studies. This report quantifies the relative accuracy of various multi-heterogeneity treatments in whole-core 3D models for parametric studies of Generation IV Pebble Bed Modular Reactors as well as provide

preliminary results of the PBMR performance analysis. Data is gathered from two different models, one based upon a benchmark for the African PBMR-400 design, and another based on the PROTEUS criticality experiment, since the African design is a more realistic power reactor, but the PROTEUS experiment model can be used for calculations that cannot be performed on the more complex model. Early data was used to refine final models, and the resulting final models were used to conduct parametric studies on composition and geometry optimization based on pebble bed reactor physics in order to improve fuel utilization.

DEDICATION

To everyone at Texas A&M University, it has been a great four years.

ACKNOWLEDGMENTS

The author would like to thank Ayodeji Alajo, Tom Lewis, and David Ames for their help with SCALE 6. In addition, I would like to thank Aaron Osborne and Ayodeji Alajo for the MCNP work included in this thesis. Next, I would like to thank the USRG program that has sponsored the beginning of this research. In addition, I also appreciate the support of the ORNL, particularly my mentor Germina Ilas, who gave me the opportunity to expand upon my research in a national lab environment. Megan Pritchard also made important contributions with her previous work. Finally, I would like to thank my advisor Pavel Tsvetkov for his support of my academic career and for funding my research.

NOMENCLATURE

HCP	Hexagonal Close Packed
HPP	Hexagonal Point-to-Point
ORNL	Oak Ridge National Laboratory
P&T	Partitioning and Transmutation
PBMR	Pebble Bed Modular Reactor
PWR	Pressurized Water Reactor
TRUs	Transuranic Nuclides
VHTR	Very High Temperature Reactor

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CHAPTER I

INTRODUCTION

The VHTR is one of six designs that have been selected for additional analysis as part of the Generation IV Nuclear Energy Systems program. A particular type of this reactor that has received attention recently is the PMBR-400. This project has begun shifting from initial goals of utilizing extreme temperatures to produce hydrogen to becoming a reactor that can effectively fulfill the needs of developing countries requiring small to medium sized reactors, while potentially minimizing nuclear waste through P&T of TRUs [Koster 2003]. The PMBR-400 can fulfill these requirements, and utilize the additional fuel generated by P&T to extend the reactor lifetime.

Due to the need for code-to-code and, more importantly, code-to-benchmark comparisons to validate this new design, a variety of modeling approaches is necessary. A range of techniques can be used to create models, and each approach or approximation has a slightly different effect on accuracy and precision. This report analyzes a few key cases, and shows how alterations to model parameters to reduce runtime or to create close relationships between models in different programs, such as SCALE 6 and MCNPX, influences results. Once the level of accuracy has been determined to show

This thesis follows the style of *Nuclear Engineering and Design*.

that the results appear consistent with reality, or at least with other models, it is possible to analyze variations to determine the details of the reactor physics.

Two models were used to analyze the physics of pebble fuel. The PBMR-400 model is based on a commercial design that was extensively benchmarked. This design has detailed information and is a useful design to vary parameters on, since it represents a real commercial design. The large number of pebbles and their random positions, however, make certain types of analysis difficult with this model. To supplement this, models of the PROTEUS criticality experiment, which used a limited number of pebbles placed in deterministic arrangements, were useful. In these cases, while the particle nature of the fuel still cannot be explicitly modeled, the pebbles themselves can be modeled and arranged individually, allowing for analysis of the impact of modeling treatments that must homogenize that region. The combined analysis of the results of these models gives a more complete understanding of the reactor physics [Tsvetkov 2004 and Pritchard 2006]. The goal of this project is to utilize knowledge of reactor physics gained from these studies and to apply it to optimize fuel composition and geometry to improve the efficiency of the fuel cycle.

CHAPTER II

METHODS

PBMR-400

Due to the limited amount of experimental data for comparison, code-to-code validation is the key when working with Generation IV VHTRs. Detailed simulations allow refinement of reactor plans while reducing the time and costs involved in prototyping and experimental analysis. To accomplish this, an automated modeling approach utilizing both Monte Carlo and deterministic approaches is necessary. In addition, these new reactor designs in particular require 3D modeling capabilities. This level of complex analysis can be performed either using recent releases of SCALE or the MCNP code. Within SCALE, the KENO VI sequence was used for simplified models and the comparison with existing benchmarks necessary for validation and verification, while the TRITON sequence was used to analyze depletion cases and power distribution necessary for more detailed modeling. It was the results of the TRITON studies that were primarily considered when analyzing composition selection and other key optimization parameters. The results of the SCALE analyses were then compared to similar models built in MCNP for additional validation.

In order to accurately model such advanced systems, however, feedback must be accounted for. The reactor dynamics needed to be analyzed by thermodynamic programs such as MELCOR as well as programs to analyze neutronics, such as SCALE

and MCNP. Due to the complexities of these processes, however, it is useful to also analyze simplified models averaging the temperature. To that end, both a Cold Core Model at 300 K and an Average Temperature Model at 973 K, the output temperature of the helium were utilized. In addition, due to the limitations of the MCNPX program that cause difficulty generating data for materials that are not at certain predetermined temperatures, a model at 1200 K was created for comparison. In addition to these temperature simplifications, the model also utilized a homogenized mixture to represent the control rods, using a precedent set by the grey curtain seen in the PMBR-400 MW OECD benchmark. After analyzing the data from these results, the depletion model was created to simulate the power distribution and more accurately model the reactor over the course of its lifetime.

Figure 1 reveals the basic design elements used in the various models, including the geometry divisions used in all cases, but excludes the specific control scheme. *Figure 2* displays a representation of the models generated in KENO 3D that shows the core and the control scheme used for each different type of model. Finally, *Table 1* displays the PBMR design parameters and material data used for the various models. The inlet and outlet helium temperatures were used to estimate average temperatures. Helium density was based on data for the HTR-10. The homogenized mixture representing the control rod, henceforth known as the grey curtain, was based on the PMBR-400 Benchmark definition, and varied in the appropriate cells to keep the appropriate number density per

Figure 1: Basic Geometry of Models (without control rods or homogenized control mixture)

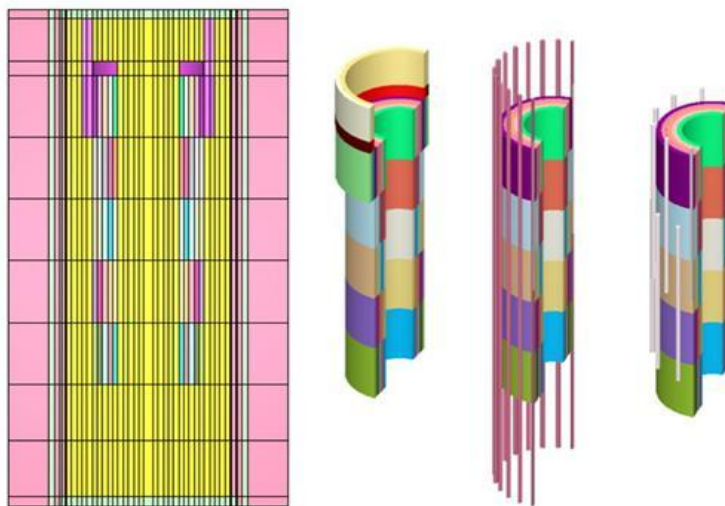


Figure 2: KENO 3D Representations of the a Whole Reactor with Grey Curtain, a Core with Grey Curtain, a Core with Control Rod Channels, and a Core with Control Rods Fully Inserted

Table 1: Key PBMR Properties [PMBR Benchmark 2007 and Sue Ion et. al. 2003]

Fuel pebble	
Fuel pebble outer radius	3.0 cm.
Thickness of fuel free zone	0.5 cm.
Total heavy metal loading per fuel pebble (equilibrium fuel)	9 g.
Fuel Enrichment	9.6 %
Fuel kernel diameter	500 micron
Kernel material type	UO ₂
UO ₂ density	10.4 g/cm ³
Kernel Coating Material	C / C / SiC / C
Layer thickness	95 / 40 / 35 / 40 μm
Layer densities	1.05 / 1.90 / 3.18 / 1.90 g/cm ³
Reflector Number Densities	
C	8.93E-02
B-10	1.00E-09
Reactor Vessel Number Densities	
Fe (Nat)	5.81E-02
Cu (Nat)	3.86E-04
Co-59	1.54E-04
Si	2.49E-04
Ni (Nat)	8.00E-03
Mo (Nat)	1.73E-03
Mn – 55	1.28E-03
Cr (Nat)	1.59E-02
Gray Curtain	
Thickness of gray-curtain region	11.5 cm
Distance from reactor center to grey curtain inner radius	7.95 cm
Control Rods	
Material: B ₄ C	2.52 g/cm ³ , 90% B-10
Effective Length	6.5 m
Number of Upper Rods	12
Maximum Depth of Upper Rods below Top Reflector	6.5 m
Number of Lower Rods	12
Maximum Depth of Lower Rods below Top Reflector	10 m
Hole Diameter	154 mm
Rod Diameter	150 mm
PCD	3943 mm
Temperatures	
He inlet temperature	773 K
He outlet temperature	1173 K

In summary, the data and tables in this section form the basis for multiple SCALE 6 models, including:

- A 300 K Reactor Model using a grey curtain for a basic analysis
- Three 973 K Reactor Models using grey curtains for an analysis at the average temperature, using various labeling criterion
 - One case with standard simplified labeling
 - One case with separate reflector labels
 - One case with independent geometrical region labels
- A 1200 K Reactor Model using a grey curtain for an analysis that can be compared to MCNPX output
- Three cases at 1200 K that use control rods instead of a gray curtain
 - One case with no rod insertion
 - One case with full rod insertion
 - One case with insertion to match the benchmark

Upon completing the above studies, the final depletion model was generated. A KENO 3D representation of this model can be seen below in *Figure 3*. This simulation used TRITON to map the power distribution in the core, and to perform advanced studies on the PBMR-400. These studies included a comparison of the multiplication factor, k_{eff} , for the standard fuel found in Table 1 and a mixture generated based on spent fuel data for a PWR, which might be considered depending upon the effectiveness of partitioning and transmutation eliminating the wastes.

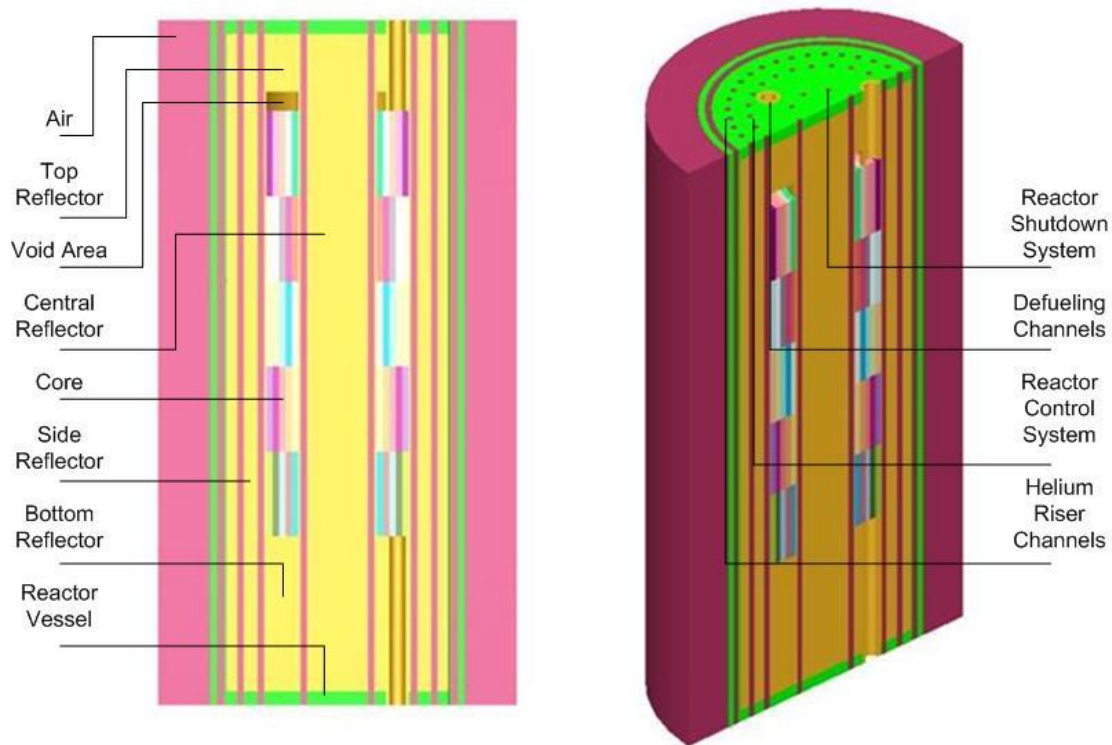


Figure 3: KENO 3D Rendering of Depletion Model

PROTEUS

The complexity of the PBMR-400 design, as well as the lack of experimental data, makes it difficult to perform certain types of analyses on its simulation, so a model of the PROTEUS criticality experiment, originally created at ORNL, was used to supplement data gathered from the PBMR-400 model. The PBMR contains thousands of pebbles in random arrangements, which must be homogenized, with special treatments to account for the neutronics impact, at both particle and pebble levels to create usable models. The PROTEUS experiment, however, developed experimental data on deterministic arrangements of a few hundred pebbles. The PROTEUS model replicates the pebble

geometry, though the particle details still require special treatments, and the fourteen different pebble arrangements available make allow for some analysis of the impact of changes in the geometry. *Figure 4* below reveals how the detailed pebble bed is constructed. The technical details, including control rod insertions, pebble bed arrangements, and compositions can be found in the NEA benchmark [NEA 2007] and IAEA report [IAEA 2001].

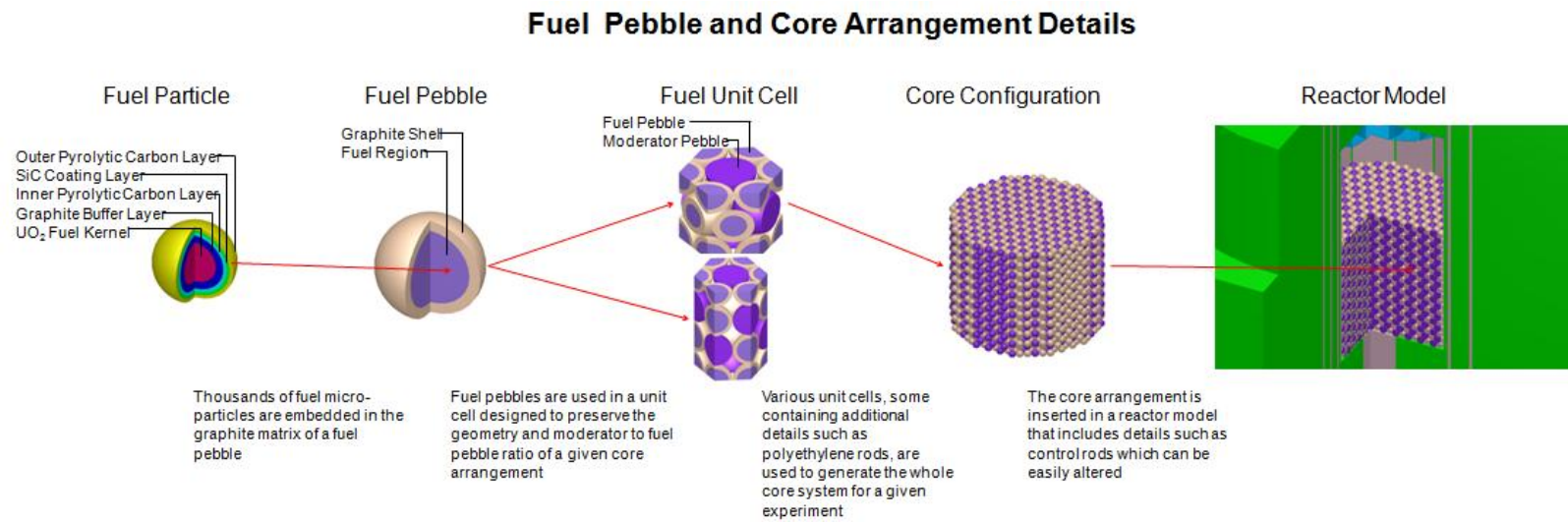


Figure 4: Details of PROTEUS Models

The KENO module of SCALE is used in the analysis, since it successfully addresses the neutronics concerns. TRITON and MELCOR are unnecessary in this system because the PROTEUS is a zero power system, so it is run with a low neutron population and does not generate enough heat to significantly affect temperature. This model is useful in studies of how explicitly modeling pebbles influences criticality and neutron flux, as well as how moderator materials in the core impact characteristics, and how the lack of a central graphite column influences the flux profile. While some comparisons to the studies conducted on the PBMR-400 are also possible using this model, it is not the primary focus of this simulation, since the differing characteristics of the commercial and experimental models prevent information from being perfectly extrapolated.

CHAPTER III

RESULTS

Grey curtain models

The grey curtain models were basic scale simulations used when first generating this model from the OECD benchmark that homogenized the control material instead of explicitly modeling the control rods. These models were utilized on a few simple analyses to determine the impact of various modeling approaches and temperature settings on the results without deviating too far from the benchmark or calculating unnecessarily detailed effects. The key data from these models all of these models can be seen below in *Table 2*.

Table 2: Key Properties of Grey Curtain Models

Model	PMBR-400 Cold Core Model (300 K)	Standard PMBR-400 Operational Temperature Model (973 K)	Reflector Division PMBR-400 Operational Temperature Model (973 K)	Individual Cell PMBR-400 Operational Temperature Model (973 K)	Standard PMBR-400 High Temperature Model (1200 K)
Best Estimate System k_{eff}	1.33228 ± 0.00062	1.25824 ± 0.00072	1.25580 ± 0.00058	1.25840 ± 0.00055	1.23915 ± 0.00054
System Mean Free Path (cm)	2.40292E+000 $\pm 1.60082E-004$	2.38192E+000 $\pm 1.48893E-004$	2.38173E+000 $\pm 1.54266E-004$	2.38072E+000 $\pm 1.44007E-004$	2.37778E+000 $\pm 1.47300E-004$
Generation Time	7.52534E-04 $\pm 1.68735E-06$	6.52334E-04 $\pm 1.33255E-06$	6.49573E-04 $\pm 1.31529E-06$	6.59729E-04 $\pm 1.41665E-06$	6.35325E-04 $\pm 1.22446E-06$

In addition to the basic criticality data, it is also important to understand the spatial flux distribution inside the core to determine what specific effects a geometrical change, such as the insertion of a reflector, might have on the reactor. *Figure 5* gives basic views of the plots of the radius, energy, and flux per unit lethargy for multiple layers of the core for one model. *Figure 6* gives a more detailed view of one of these layer plots. It also

indicates the scale used for all of the flux plots. *Figure 7, Figure 8, Figure 9, Figure 10,* and *Figure 11* show the plots of key core layers for each of the different grey curtain models. The 300 K model was used to generate cold core results, where the power generation did not cause feedback, while the 973 K models were used for more realistic calculations at operational temperatures, and the 1200 K model was used for comparison to simulations from other programs, including MCNPX. The 973 K models with different operational schemes were only used to determine if certain model approaches would create a significant bias.

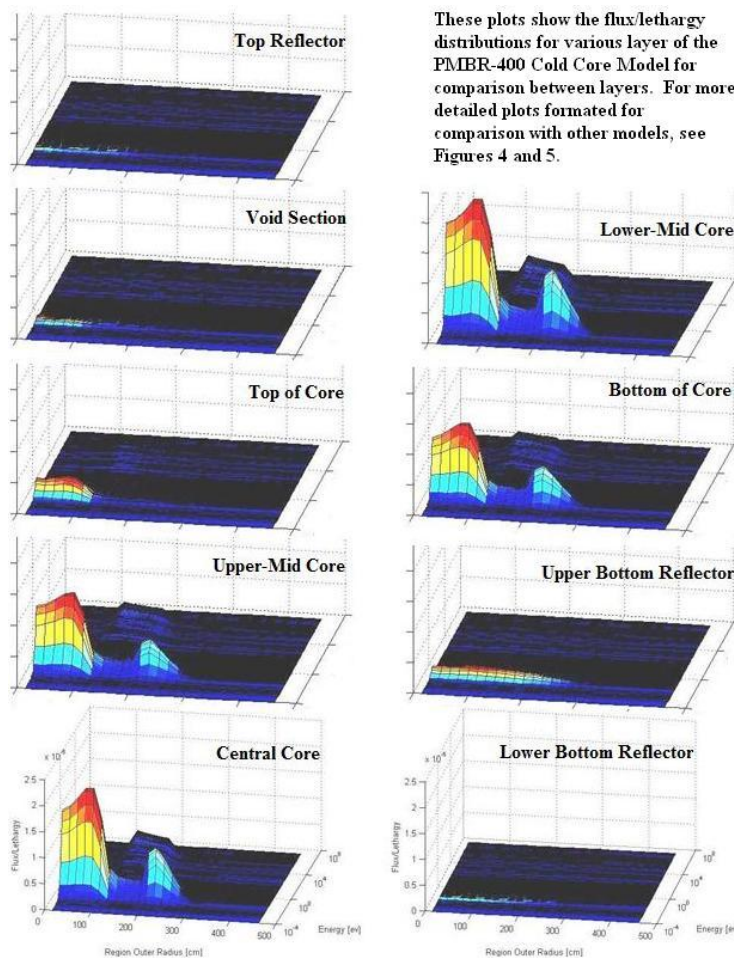


Figure 5: Cold Core Flux/Lethargy Plot for All Layers

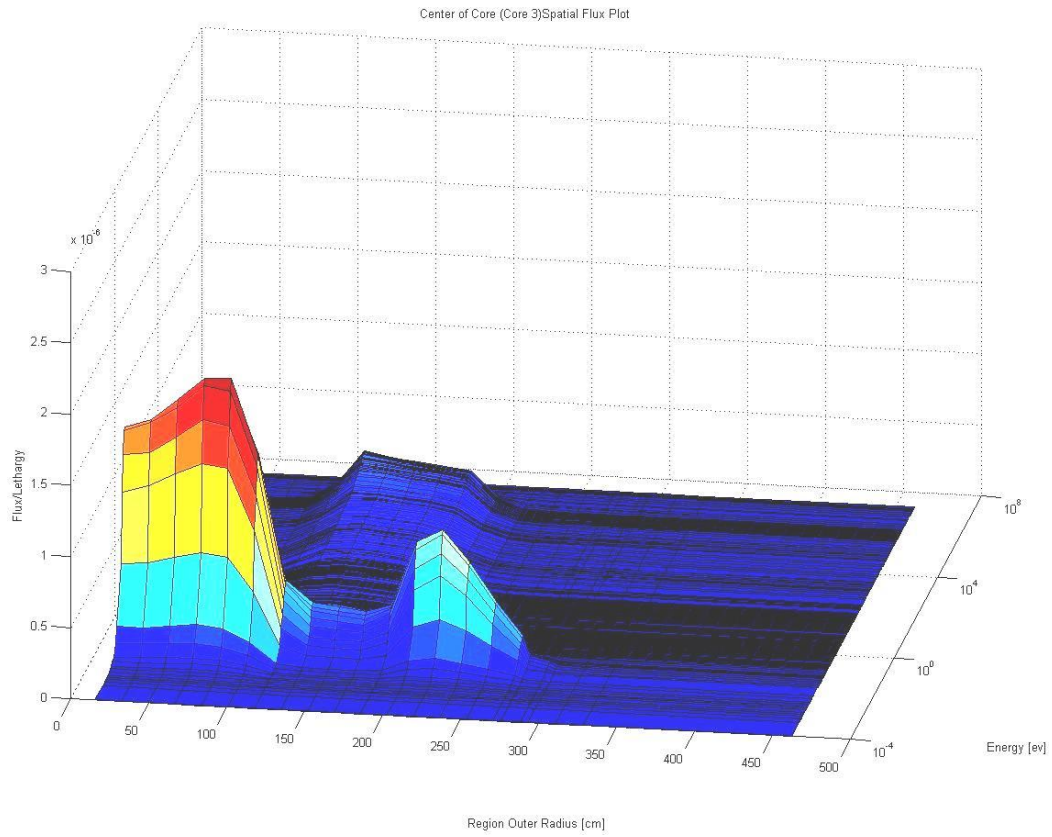


Figure 6: Detailed View of the Flux/Lethargy Plot for the Cold Core Center Layer

All of the following figures utilize the scale seen in *Figure 6*, and display the bottom of the Core (Left), Center of the Core (Center), and Top of the Core (Right):

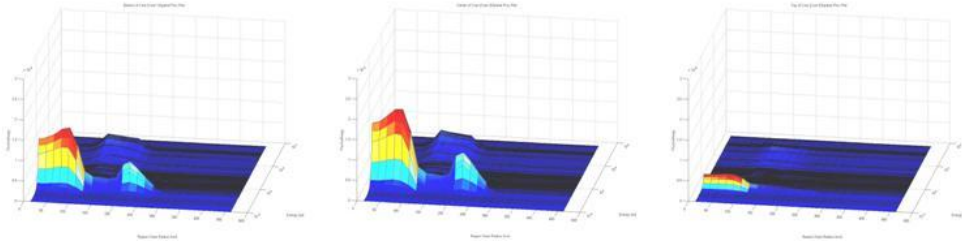


Figure 7: Cold Core Key Flux/Lethargy Plots

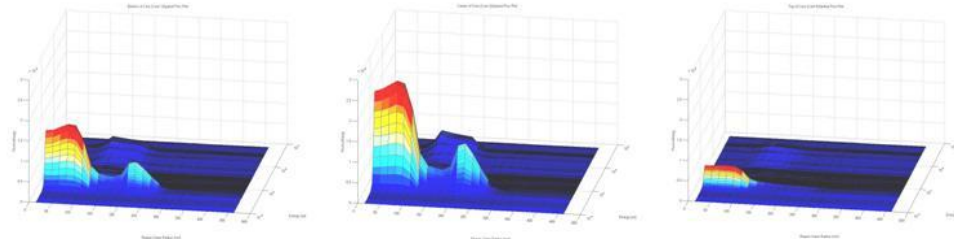


Figure 8: Operating Temperature Core, Standard Approach Key Flux/Lethargy Plots

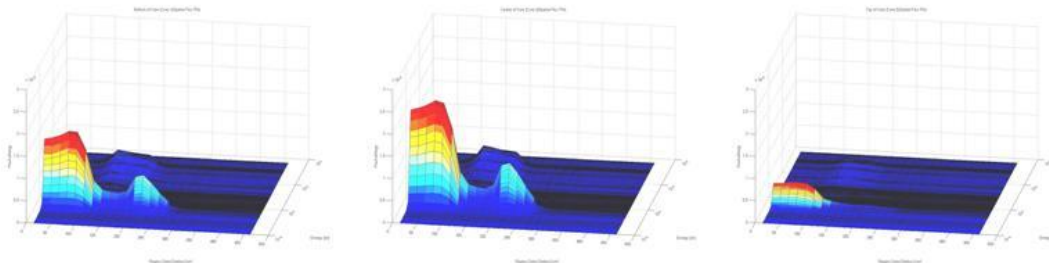


Figure 9: Operating Temperature Core, Separate Reflector Approach Key

Flux/Lethargy Plots

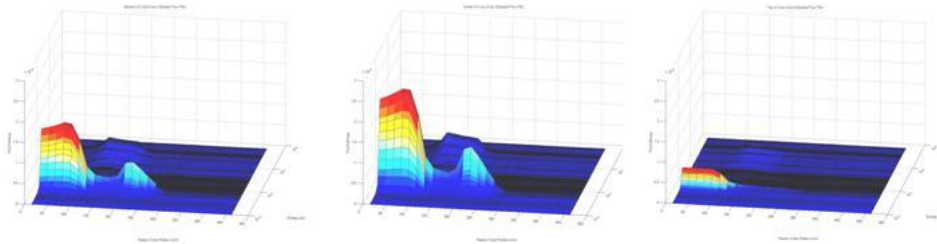


Figure 10: Key Operating Temperature Core, Individual Cell Approach Key Flux/Lethargy Plots

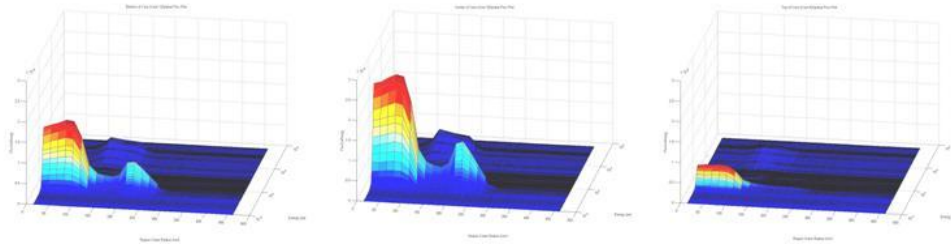


Figure 11: 1 Peak Temperature Core Key Flux/Lethargy Plots

Control rod cases

In order to more accurately depict the PMBR-400, it is necessary to use actual control rods instead of a grey curtain. While the grey curtain is a valid tool that has been used in prior studies, including the 2007 PMBR-400 Benchmark study, and the results generated from models using it are helpful for comparisons, it is important to accurately model the control rods and their arrangements for more realistic studies. Due to ongoing research, the precise details of the control rods have yet to be determined, including their B-10 content, but for this study it was estimated that 90% of the rod was B-10. Some additional details on these rods were taken from older reports to use as a baseline [Ventier et al. 2007]. The following cases were run with this more accurate geometry at 1200 K, and can be compared to similar MCNPX cases. All key data can be found in *Table 3*. In addition, the data multiplication factor for control rods fully withdrawn can be compared for a SCALE 6 model and a MCNPX Model in *Table 4*. Detailed descriptions of the individual models can be found below.

Table 3: Key Properties of Control Rod Models

Model	PMBR-400 Control Rods at Benchmark Insertion (1200 K)	PMBR-400 Control Rods Fully Inserted (1200 K)	PMBR-400 No Control Rods Inserted (1200 K)
Best Estimate System k_{eff}	1.23931 ± 0.00055	1.19938 ± 0.00062	1.23964 ± 0.00055
System Mean Free Path (cm)	$2.42224E+000 \pm 2.02895E-004$	$2.39957E+000 \pm 1.94914E-004$	$2.42376E+000 \pm 1.92655E-004$
Generation Time	$6.57505E-04 \pm 1.24547E-06$	$6.28716E-04 \pm 1.52901E-06$	$6.63425E-04 \pm 1.28682E-06$

Table 4: Comparison of SCALE 6 and MCNPX Control Rod Models

Model	SCALE 6 PMBR-400 No Control Rods Inserted (1200 K)	MCNPX PMBR-400 No Control Rods Inserted (1200 K)
Best Estimate System k_{eff}	1.23964 ± 0.00055	1.39230 ± 0.00095

Benchmark Insertion

In this case the 12 lower rods are inserted to a depth of 200 cm below the top reflector, while the 12 upper rods are inserted to the bottom of the top iron plate. This setup mirrors the depth of the grey curtain seen in the PMBR-400 Benchmark Definition, and creates a setup comparable to the 1200 K grey curtain model. The flux plots for this setup are available in *Figure 12*.

Full insertion

In this case, all control rods are inserted to their maximal depth in order to minimize the multiplication factor. Since this model uses high B-10 concentration control rods, this result approaches the minimum k_{eff} that the control rods can cause with the current parameters. Feedback mechanisms, the reactor shutdown system, and other passive safety features are not accounted for in this model. The flux plots for this setup are available in *Figure 13*.

No control rods in the core

In this case, all control rods are fully withdrawn from the core in order to maximize the multiplication factor and to quantify the excess reactivity seen in the reactor to optimize the control system. The excess reactivity was calculated to be approximately 0.1933.

Since this case does not rely on the concentration of B-10 in the control rods, it is influenced by fewer variable parameters and provides data with a more widespread application to the PMBR design. The flux plots for this setup are available in *Figure 14*.

MCNPX case

In this case, as in the SCALE 6 case with all control rods fully withdrawn, the control rod channels are explicitly modeled. The primary difference in the two models is that the MCNPX model uses a Body-Centered Cubic (BCC) structure to explicitly model the fuel pebbles, while the SCALE 6 Model creates a homogenized mixture representative of the fuel pebble schematic and fills each annular section with this mixture accounting for double heterogeneity through specialized procedure at the cross section processing stages.

All of the following figures utilize the scale seen in *Figure 6*, and display the Bottom of the Core (Left), Center of the Core (Center), and Top of the Core (Right):

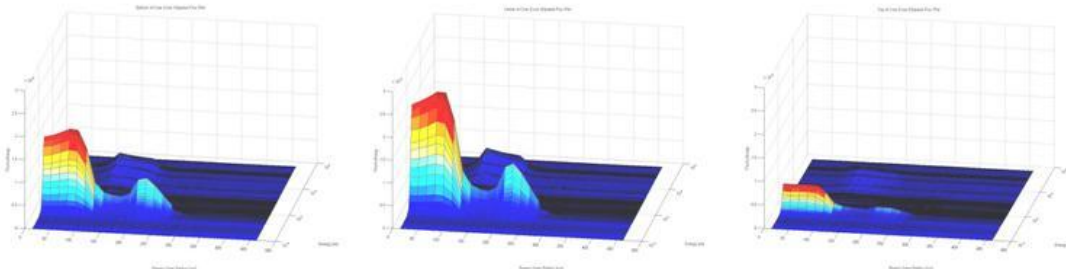


Figure 12: Peak Temperature Core, Control Rods at Benchmark Insertion Key

Flux/Lethargy Plots

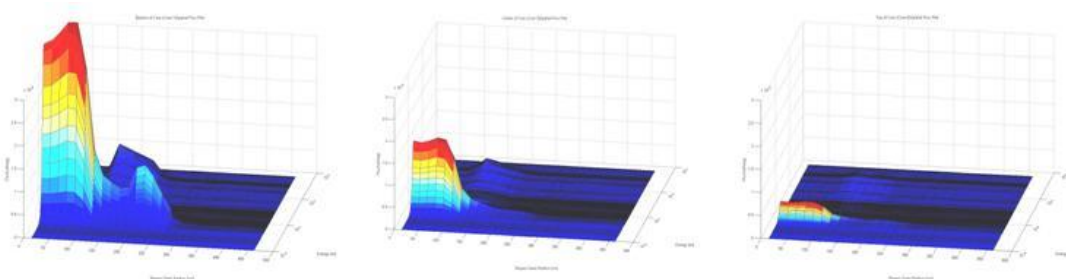


Figure 13: Peak Temperature Core, Control Rods at Full Insertion Key Flux/Lethargy

Plots

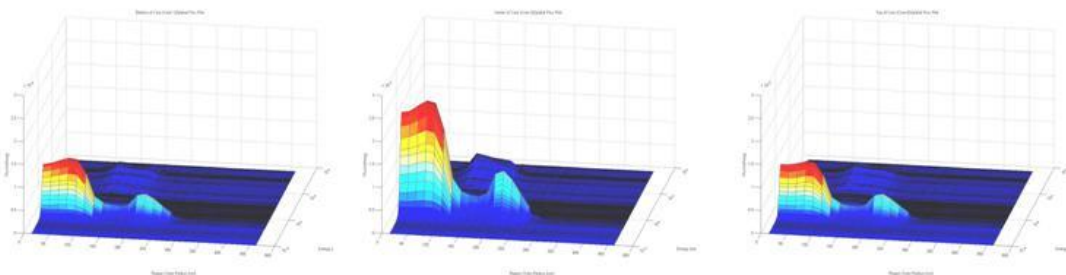


Figure 14: Peak Temperature Core, Control Rods at Full Withdrawal Key

Flux/Lethargy Plots

Depletion cases

The final model was generated using the results from the above grey curtain and control rod cases, and its details can be found in Chapter II. In this case, two different compositions were used in simulations that had identical geometric and thermal properties. The TRITON module of SCALE was used in conjunction with the different doubly heterogeneous mixtures used to represent the fuel in order to generate a power distribution plot for these cases, which can be seen below in *Figure 15*. The fuel lifetime is also approximated using the plots of the lifetime versus multiplication factor found in *Figure 16*, *Figure 17*, and *Figure 18*. This demonstrated that both fuels experienced similar power profiles and lifetimes, through the excess reactivity of the fresh fuel decreased faster than the reprocessed fuel excess reactivity.

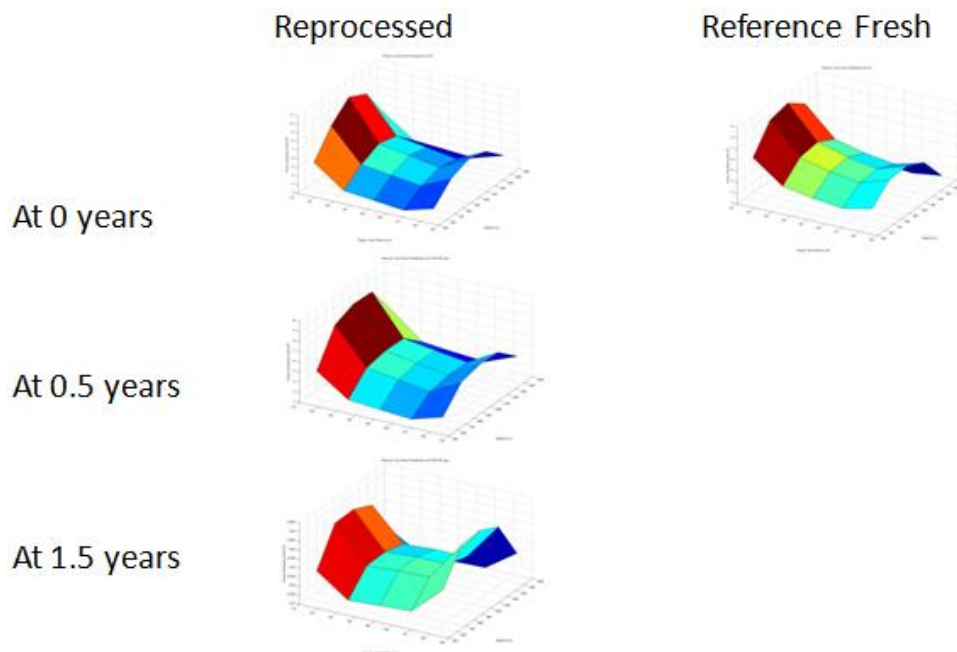


Figure 15: Volumetric Power Distribution [W/cm^3] for Various Compositions and Times

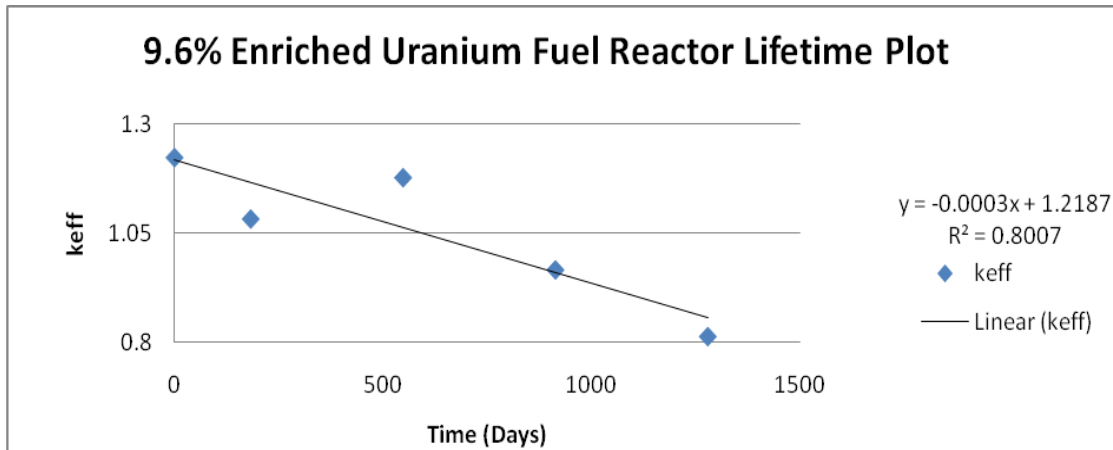


Figure 16: Multiplication Factor as a Function of Time for 9.6% Enriched Fuel

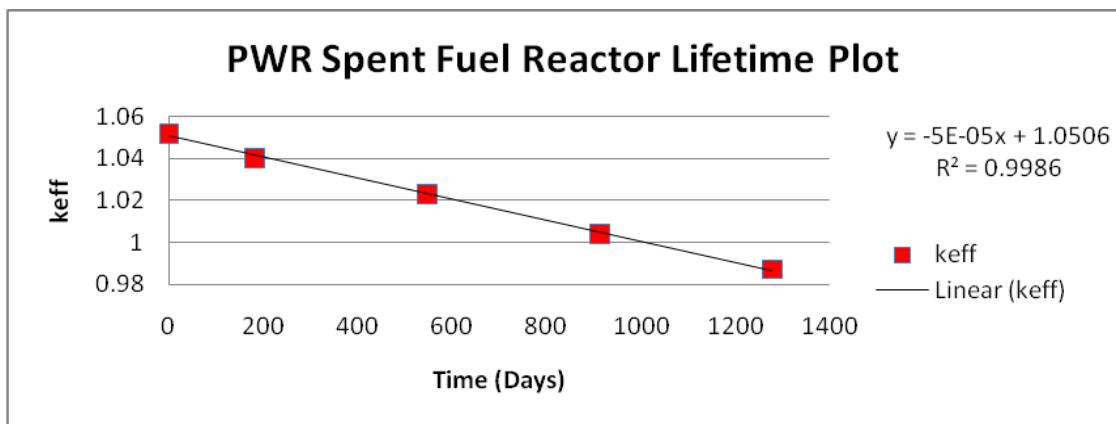


Figure 17: Multiplication Factor as a Function of Time for Reprocessed Fuel

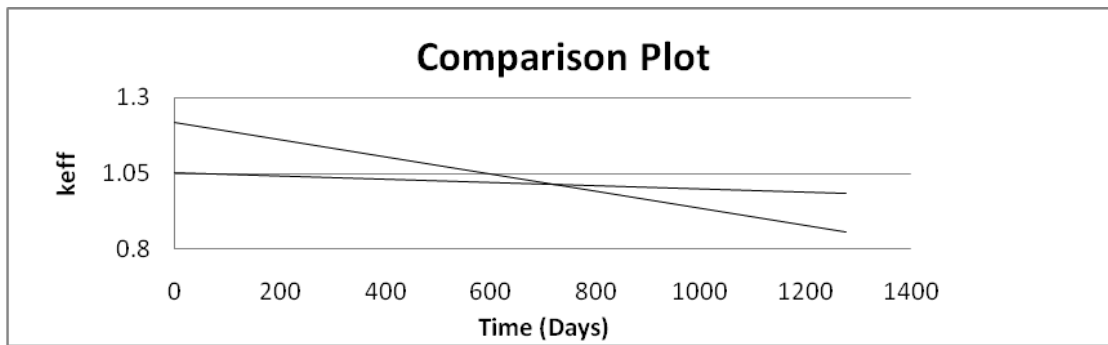


Figure 18: Comparison of Lifetime of Standard and Reprocessed Fuel

PROTEUS cases

Basic criticality information was collected for fourteen different PROTEUS cases with different core arrangements and control rod insertions in order to demonstrate that the simulation was accurately modeling the benchmark, and differed from the experimental results primarily due to making the same assumptions as the benchmark. This information can be found below in *Table 6*. Details of individual cores may be found in the NEA report [2009] on the PROTEUS experiment, though those details relevant to the results will be discussed here. Additional information, including control rod details and additional information on the polyethylene used in some core configurations can be found in the reports by Difilippo [2003] and Chawala [2002]. Using these models as a base, a few parametric studies were performed to determine the impact of certain geometry effects. Modeling the pebbles themselves did have a reasonably large impact, as shown in by the difference in the k_{eff} values of a core where the double heterogeneous mixture representing the pebbles was simply used to fill the core, which are found in *Table 7*, and the values of the explicitly modeled cases seen in *Table 6*. It should be noted that due to other differences the exact reactivity change is not determined, but the large reactivity change does indicate a strong impact, which most likely also influences the PBMR models. The impact of changing fuel to moderator ratios and packing fractions, due to the difference between HCP and HPP cells, can also be seen to some extent in the differences between the values in *Table 6*.

Table 5: Comparison of Simulations to Benchmark and Experimental Results

	Core	1	1A (1)	1A (2)	2	3
Model (HCP)	k_{eff}	1.00850	1.01014	1.00955	1.01048	1.01007
	Uncertainty	0.00130	0.00085	0.00096	0.00074	0.00085
Bench	k_{eff}	1.00767	1.00725	1.00753	1.00845	1.00818
	Uncertainty	0.00022	0.00021	0.00017	0.00023	0.00022
	Difference [pcm]	83	289	202	203	189
	Dif Uncertainty [pcm]	152	106	113	97	107
	Percent Difference	0.082368	0.28691983	0.200490308	0.201299023	0.187466524
Experiment	k_{eff}	1.00316	1.00291	1.00371	1.00243	1.00054
	Uncertainty	0.00022	0.00024	0.00072	0.00022	0.00018
	Difference [pcm]	534	723	584	805	953
	Dif Uncertainty [pcm]	152	109	168	96	103
	Percent Difference	0.532318	0.72090217	0.581841369	0.803048592	0.952485658

Table 5 (continued)

	Core	5 (1)	5 (2)	5 (3)	6	7	8	9 (1)	9 (2)	10
Model (HPP)	k_{eff}	1.00784	1.00770	1.00904	1.01315	1.00935	1.00791	1.00651	1.00761	1.00928
	Uncertainty	0.00099	0.00120	0.00076	0.00092	0.00075	0.00084	0.00091	0.00085	0.00082
Bench	k_{eff}	1.00338	1.00286	1.00333	1.00676	1.00678	1.00370	1.00299	1.00325	1.00426
	Uncertainty	0.00018	0.00019	0.00021	0.00017	0.00017	0.00019	0.00019	0.00019	0.00018
	Difference [pcm]	446	484	571	639	257	421	352	436	502
	Dif Uncertainty [pcm]	117	139	97	109	92	103	110	104	100
	Percent Difference	0.444497598	0.48261971	0.569104881	0.634709365	0.255269274	0.419448042	0.350951	0.434588	0.499871
Experiment	k_{eff}	1.00071	1.00071	1.00071	1.00053	1.00053	1.00071	1.00108	1.00108	1.00073
	Uncertainty	0.00014	0.00014	0.00014	0.00024	0.00024	0.00014	0.00024	0.00024	0.00014
	Difference [pcm]	713	699	833	1262	882	720	543	653	855
	Dif Uncertainty [pcm]	113	134	90	116	99	98	115	109	96
	Percent Difference	0.712494129	0.69850406	0.83240899	1.261331494	0.881532788	0.719489163	0.542414	0.652296	0.854376

Table 6: Homogenized Core Results for Comparison

	k_{eff}	Uncertainty
Homogenized Core	1.198	0.002

Discussion

The grey curtain simulations indicate that the modeling approach has a negligible impact on the basic results, but that the temperature is significant. This result allowed the use of the 25 different mixture cells used in the depletion model for power mapping, but also indicates that the results need to be coupled to a program that can handle the basic thermodynamics of the model, such as MELCOR. The control rod results indicate an excess reactivity of 0.1933. This may be partly due to the homogenized mixtures being used to represent the fuel, as indicated by the PROTEUS results, but the high enrichment, fresh fuel also contributes to this value, since in the real reactor, slightly lower enrichment pebbles may be used for startup. In addition, certain changes in the flux profiles between these different results sets indicate the usefulness of attempting to explicitly model to the control system. The depletion results indicate that both the given fuel enrichment and the spent fuel reprocessed mixture function to a similar maximum lifetime value, but that the excess reactivity of the fresh fuel depletes faster. This is most likely due to the lack of fertile TRUs in the fresh fuel. Overall, the results indicate that reprocessed fuel may be of interest in the PBMR design, but indications from the PROTEUS results and early models indicate that more detail is necessary to generate conclusive findings. These models do, however, help to improve the overall understanding of reactor physics in pebble bed designs and to develop optimization strategies.

CHAPTER IV

CONCLUSIONS

In conclusion, these simulations were used to perform comparisons on different fuel types in order to determine the ability to improve the efficiency of the fuel cycle. Two different materials were used, a standard 9.6% enriched fuel recommended for the PBMR operation and a composition based on reprocessed PWR fuel. The power profiles and the lifetimes of these materials were compared, and it was revealed that the reprocessed fuel had less initial excess reactivity, but still was usable for a comparable lifetime, most likely due to the TRU inventory. To complement these models, a number of supplemental simulations were performed. Models using a grey curtain, a mixture homogenizing control materials, were compared to determine the impact of temperature and different modeling techniques. Using additional data, models with control rods were created to determine the impact of control rod insertions and of the modeling program used. Additional models based on the PROTEUS cores were used to determine the effect of packing fraction, pebble positioning, and treating the pebbles in a reactor as a homogenized mixture.

Optimization of fresh uranium consumption improves reactor impact in global fuel cycle scenarios and nuclear sustainability. While additional work remains to determine the ideal configuration for a pebble bed core, this study indicates that it is possible to use a reprocessed mixture to reduce uranium consumption without significant impacting the

lifetime. Ideally future research will work to explicitly model pebble motion in the core, the impact of the pebble geometry, and a detailed temperature distribution.

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